

compared to those of passage holes formed in a conventional chevron-outlet shape. In other words, features **216** (which could be thought of as a single feature as well) form a “hood” above the troughs, for some of the embodiments in which the multi-plunge technique is used. While such a hood might be present to some extent in the chevron shapes known in the art, e.g., those in the Lee et al patent discussed above, a hood of this size and shape does not appear to have been known previously. In some embodiments, the hood exhibits a greater curvature in the upper surface region of the film hole, as compared to the previously known chevron shapes. Moreover, in some preferred embodiments, the total surface area of the hood is at least about 20% of the total surface area of the troughs, e.g., as shown in FIG. 12. In the case of a high-temperature substrate, the modified geometry of this “hood zone” may promote greater attachment of a film coolant to the outer surface (the “hot surface”) adjacent the exit hole, i.e., attachment for a longer distance along the surface.

[0070] In some embodiments, the passage holes of the present invention can also be formed successfully by using an electric discharge machining (EDM) technique. EDM techniques are known in the art, and described in a number of references, such as U.S. Pat. No. 6,969,817 (Martin Kin-Fei Lee et al); incorporated herein by reference. The techniques are sometimes referred to as “EDM milling”; “spark machining” or “spark eroding”. In general, EDM can be used to obtain a desired shape in a substrate or workpiece, by way of a series of rapidly recurring current discharges. The discharges originate between two electrodes, separated by a dielectric liquid, and subject to an electric voltage.

[0071] As a more specific example for some types of EDM equipment, a DC voltage can be applied to a drill electrode, and the desired section of the substrate is eroded by a spark formation in a gap between the drill electrode and the substrate surface. A dielectric liquid is usually forced into the gap between the electrode and the workpiece. Typically, EDM drilling machines use water (e.g., non-conductive, deionized water) as the working fluid. The material removal process is partly spark erosion and partly electrochemical. In general, the workpiece conductivity requirements prevent the use of an EDM process for substrates which are covered by non-conductive materials, such as ceramic (TBC) overcoats. Other details regarding EDM equipment, and operation settings for using the equipment, will be known to those skilled in the electromachining arts.

[0072] For most embodiments of the present invention, the EDM electrode is directed to the substrate in a sweeping motion, as described previously. The motion can be directed along the pathways illustrated in FIG. 11, or a different pathway can be chosen. As in the case of the water jet cutting process, the EDM machinery can be controlled by a multi-axis computer numerically controlled (CNC) unit. These units can direct the electrode along full 2- and 3-dimensional pathways, along with permitting movement on one or more rotational axes.

[0073] One, non-limiting example of an EDM apparatus suitable for the present invention is depicted in FIG. 13. Many elements of such an apparatus are also set forth in the Kin-Fei Lee patent referenced previously. Apparatus **220** includes a head assembly **222**. The function and detail regarding the head assembly are known in the art (e.g., FIG. 3 of U.S. Pat. No. 9,969,817), and need not be discussed in detail here. An electromagnet **224** is coupled to a slide assembly **226**, by way of an adaptor plate **228**. A first manual slide **230** is coupled to

the slide assembly adaptor plate. The manual slide **230** allows an operator to position the head assembly **222** after the apparatus has been attached to a substrate, e.g., an outer surface of a turbine blade, via the electromagnet **224**, or by way of some other conventional attachment mechanism.

[0074] A second manual slide **232** is operatively coupled to the first manual slide **230**, and may be configured to provide perpendicular translation of the head assembly **222** with respect to the first manual slide **230**. The second slide **232** is operatively coupled to a mini tilt and swivel vice **234**. The mini tilt and swivel vice **234** allows for rotation of the head assembly **222** in both directions illustrated by the curved arrow **236**. Vice **234** also allows for an angular tilting of the head assembly **222**. (This angular tilting is represented by the arrow **238**). Although manual slides and mini tilt and swivel vices are discussed in this embodiment, it should be understood that any mechanism that allows for the positioning of the head assembly **222** relative to a surface or area to be drilled and/or milled (e.g., any CNC device) would be equivalents that may be used in various embodiments of the disclosed apparatus.

[0075] In a typical EDM apparatus which can be used for the present invention, a holder **240** is employed to fasten and guide the movement of a consumable, wire electrode **242**. Various types of holders and electrodes for EDM systems are available commercially. One source is Aerospace Techniques, Middletown, Conn. The wire electrode, fed through apparatus **220**, can be directed by the programming associated with the apparatus to precisely form the passage hole/exit geometry required for this invention.

[0076] In other embodiments, the passage holes of the present invention can be formed successfully by using a laser system, e.g., a laser drilling apparatus. In preferred embodiments, the laser source employs at least one pulsed laser beam. Such a system is described in patent application Ser. No. 12/435,547 (Bunker et al), filed May 5, 2009, which is incorporated herein by reference. Usually (though not always), the pulsed laser beam includes a pulse duration including a range less than about 50 μ s, an energy per pulse having a range less than about 0.1 Joule, and a repetition rate with a range greater than about 1000 Hz. The system can also include a variety of other elements, such as a control subsystem coupled to the laser source, configured to synchronize the position of the substrate with the pulse duration and energy level. Such a control subsystem is advantageous when forming the passage holes and exit hole geometries through coatings applied over the substrate.

[0077] FIG. 14 is a schematic illustration of a laser-based system for producing at least one passage hole according to embodiments of this invention. The system **250** includes a laser source **252**, outputting a pulsed laser beam **254**. The laser source **252** usually has a pulse duration less than about 50 μ s, with an energy-per-pulse value of less than about 0.1 Joule. The pulses are typically activated with a repetition rate greater than about 1000 Hz. In one embodiment, the wavelength of the laser beam **254** is in a range between about 200 nm to about 1100 nm. In another embodiment, the average power of the laser beam is larger than about 20W, with a desirable beam quality to focus down to spot sizes less than about 200 microns.

[0078] In an exemplary embodiment, the pulse duration is between about 10 μ s and about 200 ns. In another embodiment, the pulse duration is between about 50 μ s and about 1 femto second. With such a laser, a wide range of laser inten-